

Internal chemo-dynamical Modeling of Gas Exchange within Galaxies and with their Environment

Gerhard Hensler¹, Simone Recchi^{1,2}, Danica Kroeger³, Tim Freyer³

¹ *Institute of Astronomy, University of Vienna, Türkenschanzstr. 17, 1180 Vienna, Austria, email: hensler@astro.univie.ac.at*

² *INAF - Osservatorio Astronomico di Trieste, 34131 Trieste, Italy*

³ *Inst. of Theor. Physics & Astroph., U of Kiel, 24098 Kiel, Germany*

Abstract.

By a few but important examples as models of combined radiative and wind-driven HII regions and galactic winds we demonstrate the importance of refined small-to-medium scale studies of chemo-dynamical effects. These processes determine the internal dynamics and energetic of the ISM and affect its observational signatures, e.g. by abundance contributions, but are not yet reliably and satisfactorily explored.

1. Introduction

Galaxies experience energy deposit and element release into their ISM from massive stars during the lives and by their explosions. They are main drivers of energetics and dynamics in galaxies and in both stages they release characteristic elements which are preferably contained in the hot gas phase. Nevertheless, because of the close coupling of hot, warm, and cool ISM energetic and dynamical processes lead to chemo-dynamical effects which alter the energy budget and the element content in the different gas phases. Understanding these processes from stellar to galactic scales are therefore vital for understanding and modeling the evolution of galaxies and also their interaction with the environment.

2. Massive Stars

2.1. Effects of massive stars during their lives

Massive stars play a crucial role in the evolution of galaxies, as they are the primary source of metals, and they dominate the turbulent energy input into the interstellar medium (ISM) by their massive and fast stellar winds, the ultra-violet radiation, and supernova explosions. The radiation field of these stars, at first, photo-dissociates the ambient molecular gas and forms a so-called photo-dissociation region (PDR) of neutral hydrogen. Subsequently, the Lyman continuum photons of the star ionize the HI gas and produce a HII region that expands into the neutral ambient medium.

As these stars have short lifetimes of only a few million years, HII regions indicate the sites of star formation (SF) and are targets to measure the current SF rate in a galaxy. Furthermore, the emission line spectrum produced by the ionized gas allows the accurate determination of the current chemical composi-

tion of the gas in a galaxy. Although the physical processes of the line excitation are quite well understood and accurate atomic data are available, so that the spectral analysis of HII regions (see e.g. Stasińska 1979; Evans & Dopita 1987) serves as an essential tool to study the evolution of galaxies, their reliability as diagnostic tool have also to be studied with particular emphasis e.g. to temperature fluctuations (Peimbert 1967; Stasińska 2002) and line excitations.

While the simple concept of a uniform medium in ionization equilibrium with the radiation from the stars (the Strömgren sphere) is successful in describing several global features of the object and allows to predict the emission line spectrum quite reliably, it has long been realized that HII regions are complex and dynamical objects. Dynamical modelling of HII regions caused purely by the energy deposit of the stellar radiation field has therefore been started already long ago (see e.g. Yorke 1986, and references therein) providing both a first insight into the formation of dynamical structures and allowing to derive more realistic scaling laws for observational comparisons, respectively.

That massive stars do not only release energy by their radiation but also act by means of strong stellar winds which drive a turbulent ISM but, on the other hand, both are metal dependent has three major consequences for galaxies with present-day solar metallicities: at first, the classical HII has lost its simplicity, because, secondly, it engulfs a vehemently expanding stellar wind bubble (SWB) and, thirdly, peels off the stellar outermost shells, by this, incorporating nuclear burning regions into the wind mass loss.

2.2. Star formation Feedback

Quiescent SF as a self-regulated process is a widely accepted concept. The stellar feedback can adapt both signs, positive as a triggering mechanism in a self-propagating manner like in superbubble shells (Ehlerova et al. 1997; Fukuda & Hanawa 2000) vs. negative as self-regulation. Primarily the correlation between the surface density of disk galaxies' HI gas and the vertically integrated SF rate derived from the H α flux (Kennicutt 1998) serves as the best proof of a SF self-regulation. Even more refined observations that trace more complex molecular gas (Gao & Solomon 2004) follow the same surface density relation. Surprisingly, this relation can be reproduced by different numerical models and with different prescriptions from purely collapsing cloud cores (Li et al. 2005) via thermodynamical cloud models (Krumholz & McKee 2005) to sophisticated global chemo-dynamical treatments of galaxy models (Burkert et al. 1992; Harfst et al. 2006) and even seems to hold under the neglect of self-regulation processes in cosmological simulations (Kravtsov 2003). This fact obtrudes that the gas dependence of processes within the SF matter cycle although expected to behave non-linearly cancels out and results in a universal law. Such a dependence is e.g. plausible because Köppen et al. (1995) have demonstrated that due to the square-dependence of collisionally excited radiative cooling on the gas volume density also the SF rate adapts to that over a large density range and almost independent of the heating rate and other fiducial parameters. This also holds for a multi-phase ISM accounting for supernova typeII (SNII) production of hot gas and for gas transitions by evaporation and condensation (Köppen et al. 1998). From this result it seems reasonable that the vertical accumulation of gas mass should also lead to a SF rate dependence on the column gas density because the

self-gravitational potential determines the disk stratification. The Kennicutt law therefore could reflect a sum over the volumes, while the 1.4 power is also close to the pure free-fall criterion.. Then the timescales must definitely tell us about both process and carrier of self-regulation, respectively.

2.3. Evolution and structure of bubble around massive stars

However, this question needs more exploitation yet. Already the energy deposit by massive stars described by a parameter ϵ , called energy transfer efficiency, is neither well derived during their normal lives nor for their SNII explosions and the expanding SN remnants. The reason is that for both stages the environmental state and thus preceding processes as well as dynamical effects play a significant role. Analytical estimates for purely radiative HII regions yield ϵ of the order of a few percent (Lasker 1967). Although the additional stellar wind power L_w can be easily evaluated from model and observational values (Kudritzki & Puls 2000), its fraction that is transferred e.g. into thermal energy, i.e. the thermal ϵ , or into turbulent energy is not obvious from first principles. The picture is that the fast stellar wind creates shocks that form the SWB filled with very hot plasma, which expands into the HII region so that also this HII shell has to expand into the surrounding ISM due to its overpressure.

The structure and evolution of SWBs and the transition to its surrounding HII region can be described by a set of equations (Weaver et al. 1977) from which the wind-energy deposit can be derived theoretically under the simplifying assumptions of a point source of a constant and spherically symmetric strong wind that interacts with a homogeneous ambient ISM. The ϵ 's amount to significant fractions of L_w (see Freyer et al. 2003, and references therein). It has become evident that the stellar parameters such as the mass-loss rate, the terminal velocity, the effective temperature and the luminosity of the star vary strongly during the stellar lifetimes. While most previous studies dealt with either the evolution of HII regions or of SWBs separately and with constant values, little is known about the interaction of these two structures.

Although the analytical and semi-analytical solutions for the evolution of SWBs have been improved over the years as well as the numerical simulations have been done with increasing complexity, like e.g. 2D calculations of SWBs (see e.g. by Różyczka 1985, and a series of papers) and/or combined 1D radiation-hydrodynamical models of HII region coupled with the dynamical SWB (e.g. by García-Segura & Mac Low 1995, for references see Freyer et al. 2003), a variety of physical effects remains to be included in order to achieve a better agreement of models and observations with regard to the evolution of the hot phase in bubbles (MacLow 2000; Chu 2000).

To improve the insight into the evolution of radiation-driven + wind-blown bubbles around massive stars, we have performed a series of radiation-hydrodynamics simulations with a 2D cylindrical-symmetric nested-grid scheme for stars of masses $15 M_\odot$ (Kroeger et al. in prep.), $35 M_\odot$ (Freyer et al. 2006), $60 M_\odot$ (Freyer et al. 2003), and $85 M_\odot$ (Kroeger et al. 2007). The main issues are:

1) The HII region formed around the SWB has a complex structure mainly affected by dynamical processes like e.g. shell instabilities, vortices, mixing effects, etc. It is more compressed by stronger winds (see Fig.1).

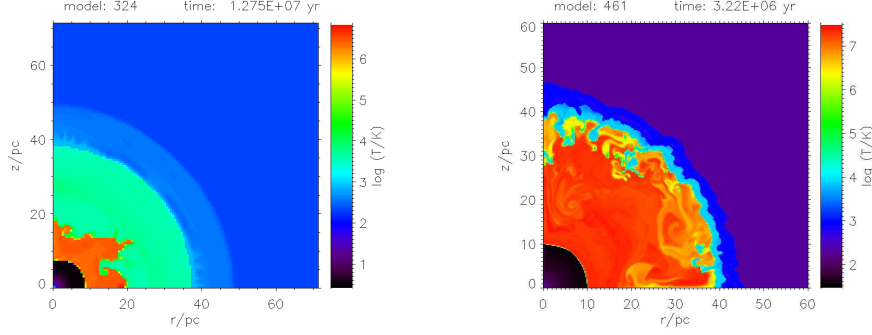


Figure 1. Temperature distributions of a $15 M_{\odot}$ (left panel) and a $85 M_{\odot}$ (right panel) model at late stages of their stellar evolution. The temperatures are colour coded to the right of the plots but differently (taken from Kroeger 2006). For discussion see text.

- 2) Finger-like and spiky structures of different densities and temperatures are formed in the photo-ionized region (Freyer et al. 2003).
- 3) The regions contributing to the HII emission line are not solely limited to the photo-ionized shell around the SWB but also form from photo-evaporated gas at the trailing surface of the SWB shock front (see $85 M_{\odot}$ model in Fig.1).
- 4) Because dispersion of this cooler photo-evaporated gas into the hot SWB leads to mixing also the stellar material expelled by the wind emerge partly in the spectra.
- 5) As a consequence the metal-enrichment of the wind in the Wolf-Rayet stage which is generally assumed to remain only in the hot SWB for a long time affects the observationally discernible abundance of the HII gas. By these models (Kroeger et al. 2006) it could be proven for the first time that the metal release by Wolf-Rayet stars can be mixed within short timescales from the hot SWB into the warm ionized gas and should become observationally accessible. As the extreme case for the $85 M_{\odot}$ star we found a 22% enhancement of Carbon, but negligible amounts for N and O.
- 6) As expected from the distribution of HII gas the radially projected H α brightness shows a decrease to the center and a slight brightening to the limb but not as strong as expected according to the increase of the line-of-sight with impact parameter (Freyer et al. 2003). This effect depends on the bubble age and starts from central brightening. It also demonstrates both: the neglect of heat conduction and the homogeneous initial density do not allow a sufficient brightening of heat conductive interfaces so that, secondly, only the photo-evaporated backflow can contribute to the H α luminosity in present models. In reality, condensations which become embedded into the hot SWB are exposed to heat conduction.
- 7) The sweep-up of the slow red supergiant wind by the fast Wolf-Rayet wind produces remarkable morphological structures and emission signatures which agree well with observed X-ray luminosity and temperature as well as with the limb brightening of the radially projected X-ray intensity profile (for details see Freyer et al. 2006).
- 8) ϵ 's for both radiative as well as kinetic energies remain much lower than analytically derived (more than one order of magnitude) and amount to only a

few per mil (Hensler 2007). There is almost no dependence on the stellar mass what is principally expected because the energy impact by Lyman continuum photons and by wind luminosity increase with stellar mass. Vice versa, since the gas compression is stronger by a more energetic wind also the energy loss by radiation is more efficient.

Nonetheless, a word of caution and unfortunately of discouragement has to be expressed here because the stellar evolutionary models are not unique but depend on the authors. In order to get a quantifiable comparison of the models by García-Segura et al. (1996a, 1996b) with our 2D radiation-hydrodynamical simulations (Freyer et al. 2003, 2006) for the 35 and 60 M_{\odot} studies we used the same stellar parameters. Since no stellar parameters were available from the same group for the 15 and 85 M_{\odot} models we had to make use of the Geneva models (Schaller et al. 1992). A comparison of the age-dependent 60 M_{\odot} parameters of both groups has revealed enormous differences in the energetics by almost one order of magnitude as well as that the Wolf-Rayet and Luminous Blue Variable stages occur in contrary sequence, respectively (Kroeger 2006).

Furthermore, HII regions show a great diversity of shapes which give direct evidence that the ISM is not a smooth, homogeneous, and uniform medium. In addition, the complexity of the internal structure and of the flow pattern of the gas indicates that the evolution of the ionized region is strongly affected by existing irregularities and hydrodynamical instabilities. And even more, stellar wind bubbles and SNRs of neighbouring stars collide and may overlap to form superbubbles with diameters of several 100 pc scale, which are prominent by their X-ray emission in galaxies with active SF. This picture of SWB/HII aggregates has also to be extended by PDRs which are mainly produced in the early evolutionary phases of ultra-compact HII regions. Since they are heavily dust-enshrouded they emerge from GLIMPSE observations (Benjamin et al. 2003) and allow detailed diagnostics of these common stellar bubbles (Chruchwell et al. 2006).

3. Galactic Mass Exchange

3.1. Galactic Outflows

Finally, massive stars explode as SNeII, creating a SN remnant that sweeps up the ambient medium. These phases have been understood and modeled in detail energetically and dynamically. Cumulative SNeII form superbubbles which expand vehemently and can drive a galactic outflow. Since the hot superbubble gas carries SNII elements and has to act dynamically with the surrounding ISM, it has huge energetic and chemical effects on galaxies. Therefore, the questions that arise for their chemo-dynamical contribution to galaxy evolution are the same as before for the HII /SWB regions. Although investigations have been performed for ϵ of SNe (Thornton et al. 1998) and superbubbles (e.g. Strickland et al. 2004) they are yet too simplistic (e.g. only 1D) for quantitative results.

Because of their low gravitational potential dwarf galaxies are sensitive to energetic processes like superbubbles so that these can easily develop to a galactic outflow as perceivable e.g. in NGC 1705 (Hensler et al. 1998), NGC 1569 (Martin et al. 2002), I Zw 18 (Martin 1996), and many other Blue Compact Dwarf Galaxies (BCDs). Dynamical models (MacLow & Ferrara 1999) can still

provide only a qualitative understanding. Nevertheless, the element abundances stemming from different stellar progenitors should enable one to trace back the history of element enhancement vs. depletion by different processes. Since in general the SF varies in BCDs and, furthermore, produces massive star clusters one can imagine that a first superbubble has to exert most of its energy for its expansion while the successive SNII explosions can be funneled through the chimney and by this more easily expel its metal-enriched gas. This can only happen, if the next SF episode follows shortly enough after the former one. For this scenario it is, thus, important to explore the timescale of refill superbubbles vs. the SF timescale. For the refill of superbubbles in the gas layer of typical BCDs we (Recchi & Hensler 2006) found a range of a few 100 Myrs. This means, that the amount of galactic winds depends not only on the SF rate but also on its modes, bursting vs. gasping, but affects the chemo-dynamical evolution (Hensler & Rieschick 2002).

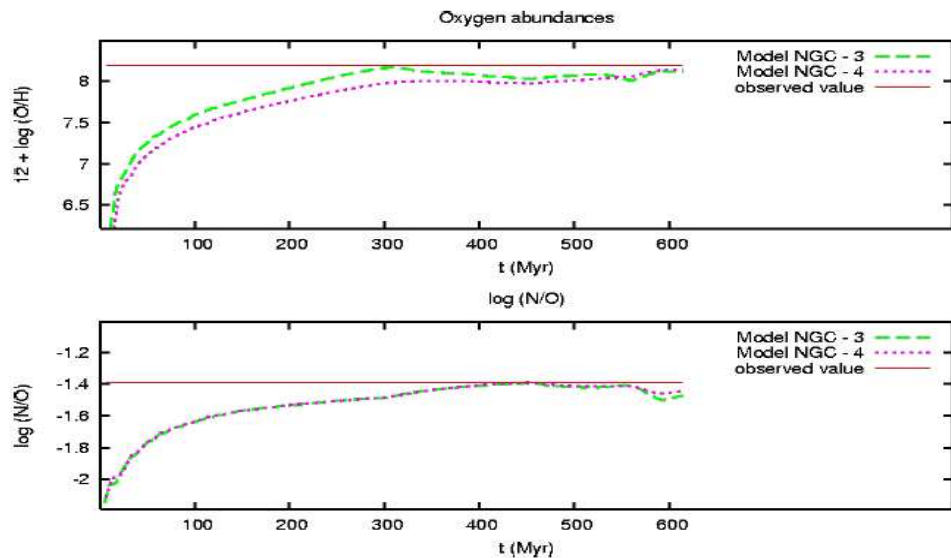


Figure 2. Comparison of abundance evolution in 2 models representing NGC 1569: NGC-3 with a single strong and short SF burst, NGC-4 with 2 former SF epochs and a mild recent burst. (For details see Recchi & Hensler 2006).

For the best studied BCDs, I Zw 18 (Recchi et al. 2004) and NGC 1569 (Recchi et al. 2006), 2D dynamical models with characteristic tracer elements have been performed aiming at achieving a best fit with observations. The main results can be briefly summarized as follows: Galactic winds always occur. Models with bursting SF are generally unable to account for the chemical and morphological properties of NGC 1569, because they either underproduce O or inject too much energy into the system, enough to loose a too large gas fraction. The best agreement with the chemical composition is found for long-lasting continuous episodes of SF of some hundred Myrs of age and a recent more intensive short SF burst (see Fig.2). In most models with gasping SF, the final chemical composition of the galaxy reflects mostly the chemical enrichment from old stellar populations. In fact, if the first episodes of SF are powerful enough to create a

galactic wind or to heat up a large fraction of the gas surrounding the SF region, the metals produced by the last burst of SF are released into a too hot medium or are directly ejected from the galaxy through the wind. They do not have the chance to pollute the surrounding medium and to contribute to the chemical enrichment of the galaxy. This result confirms the conclusion that most of the O from the last SF epoch is stored in the hot X-ray gas (Martin et al. 2002).

3.2. Gas Infall

Although the element abundance properties of most BCDs favour only a young stellar population of at most 1-2 Gyrs, they mostly consist of an underlying old population as it is the case for NGC 1569. Furthermore, most of the objects are embedded into HI envelopes from which at least NGC 1569 definitely suffers gas infall (Stil & Israel 2002; Mühle et al. 2005). This has lead Köppen & Hensler (2005) to exploit the influence of gas infall with metal-poor gas into an old galaxy with continuous SF on particular abundance patterns. Their models could match not only the observational regime of BCDs in the $[12+\log(\text{O}/\text{H}) - \log(\text{N}/\text{O})]$ space but also explain the shark-fin shape of their data distribution by means of the ratio of mass infall to existing cloud mass in the sense that for larger infall fractions the loop is more extended.

Analytical investigations as well as too simplified numerical models, however, are unable to distinguish between the different gas phases and their metal content in order to derive abundances in the targets of observations.

In addition, also mixing effects at interfaces between gas phases and due to turbulence (like e.g. those in the combined SWB/HII complexes) contribute to the observations by the enhancement or, respectively, dilution of metals. Since gas infall is not only affecting the chemistry but also SF (Hensler et al. 2004) and dynamics of outflows we have extended the former models (Recchi et al. 2004, 2006) by infalling clouds (Recchi & Hensler 2007). In these models, two kinds of cloud contributions are considered, only initially existing and continuously formed, respectively. The issues are the following: Due to dynamical processes and thermal evaporation, the clouds survive only a few tens of Myr. The internal energy of cloudy models is typically reduced by 20 – 40 % compared to models with a smooth density distribution. The clouds delay the development of large-scale outflows, helping therefore in retaining a larger amount of gas inside the galaxy. However, especially in models with continuous creation of infalling clouds, their ram pressure pierce the expanding supershells so that through these holes freshly produced metals can more easily escape and vent into the galactic wind. Moreover, assuming for the clouds a pristine chemical composition, their interaction with the superbubble dilute the hot gas, reducing its metal content. The resulting final metallicity is therefore, in general, smaller (by $\sim 0.2 - 0.4$ dex) than the one attained by smooth models.

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